AC 2009-1073: SELF-SUFFICIENT, ENERGY-EFFICIENT HOUSE DESIGN

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Self Sufficient Energy Efficient House Design

Abstract

If energy requirements of electronic components and home appliances decline reasonably, then ambient energy scavenging and conversion could become a viable source of power for many applications. The potential ability to satisfy overall power and energy requirements of an application using ambient energy can eliminate some constraints related to conventional power sources. Recently, researchers have performed several studies in alternative energy sources that could provide high, medium and small amounts of power to electronic devices. These studies were focused to investigate and obtain power from different energy sources, such as vibration, light, wind, sound, airflow, heat, waste mechanical energy, human power and temperature variations.

The purpose of this research was to study a house of the future intended to be predominately self sufficient, energy efficient, and ambient energy powered that would generate enough energy to power the house appliances. The self powered and energy efficient house idea was investigated to explore ways to convert environmental sustainable energy sources into electrical energy. Sources of ambient (environmental) energy were determined prior to design of the house in order to construct a house of maximum efficiency from ambient energy sources as a purpose of this research. This paper served to explain the first phase of the project which was to identify ambient energy sources and group in specific categories. The sources identified and listed in the table was supported by the literature review in academia and industry. The research works have been conducted so far, support the idea of having specific energy sources to power the house. The ambient energy collected from different sources was characterized as high, medium, and low power sources. Energy generation from solar, wind, and hydroelectric power sources was categorized as high power sources. Energy from pedaled chairs (new design) and tables (new design), fitness equipments, collected gray water (from sinks, bath and rain), city water, and some furniture was categorized as medium power sources. Power generation from opening/closing of doors and cabinet drawers, floor vibrations, clocks, heat differences, etc. was categorized as low power sources. All electrical energy collected from aforementioned sources is consolidated and retained in storage devices (batteries) using specially designed electrical energy harvesting and conversion circuits.

I. Introduction

Renewable energy today provides about 9% of the world's energy and 8% to 10% of the U.S. needs[1]. However, in many parts of the world these percentages are increasing significantly. Renewable energy resources can be categorized into the forms of radiant solar, wind, hydropower, biomass, geothermal, mechanical etc. Renewable energy sources offer many advantages to an energy-hungry world. They can be used in many ways, offer minimal environmental problems, and can be harnessed with appropriate technology. These sources particularly offer hope to the developing countries who are economically disadvantaged by high energy cost. Every day, the earth receives thousands of times more energy from the sun than consumed by all other resources. Wind power is very a viable source of renewable energy where the wind is predominately available.

Sustaining the power requirement for autonomous and portable electronics systems is an important issue today. In the past, energy storage has improved significantly. However, this progress has not been able to keep up with the development of microprocessors, memory storage, and sensor applications. Ambient power sources such as replacement of batteries, come into consideration, to minimize the maintenance. Power scavenging may enable electronic devices to be completely self-sustaining or can make battery maintenance minimized. Researchers have performed wide spread studies in alternative energy sources that could provide small amounts of electricity to low-power devices. Energy harvesting can be obtained from different energy sources, such as vibration, light, acoustic, airflow, heat, and temperature variations. When augmented with the energy stored in common storage elements such as batteries, the environment may represent a relatively infinite source of energy. Consequently, energy harvesting (scavenging) methods must be characterized by their power density, rather than the energy density. Table 1 compares the estimated power and challenges of various ambient energy sources[2]. Values in the table are derived from a combination of published studies, experiments performed by the authors, theory, and information which is commonly available in textbooks. Light, for instance, can be a significant source of energy, but it is highly dependent on the application and the experience to which the device is subjected. Thermal energy, in contrast, is limited because the temperature differences across a chip are typically low. Vibration energy is a moderate source, but again dependent on the particular applications[15]. This experimental research study incorporates different disciplines to gather data on both energy reductions of the households by incorporating energy friendly devices and generating energy from the ambient energy sources.

Table 1. Comparison of power density of energy harvesting methods

Energy Source	Power Density & Performance
Acoustic Noise[3]	0.003 $\mu W/cm^3$ @ 75Db 0.96 $\mu W/cm^3$ @ 100Db
Temperature Variation[4]	10 $\mu W/cm^3$
Ambient Radio Frequency[5]	1 $\mu W/cm^2$
Ambient Light	100 mW/cm^2 (direct sun) 100 $\mu W/cm^2$ (illuminated office)
Thermoelectric[6]	60 $\mu W/cm^2$
Vibration (micro generator)[7]	4 $\mu W/cm^3$ (human motion—Hz) 800 $\mu W/cm^3$ (machines—kHz)
Vibrations (Piezoelectric)[8]	200 $\mu W/cm^3$
Airflow[9]	1 $\mu W/cm^2$
Push buttons[10]	50 $\mu J/N$
Shoe Inserts[11]	330 $\mu W/cm^2$
Hand generators[12]	30 W/kg
Heel strike[13,14]	7 W/cm^2

Such research is needed to increase the use of ambient energy sources by providing detailed information to the public about the reliability of the sources. The purpose of this research was to identify and categorize ambient energy sources in and around the house. The energy sources identified help to power house partially or fully depending on availability of the sources. Energy from all sources need to be converted to electrical energy. The second phase of the study will be designing and building of a house of the future intended to be predominately self sufficient, energy efficient, and ambient energy powered that will generate enough energy to power of the needs of the house. For this aim, a brief literature review of ambient energy sources are studied with the support of very recent research.

II. Brief Literature Review

Piezoelectric Generation: This method alters mechanical energy into electrical energy by straining a piezoelectric material[16]. Strain or deformation of a piezoelectric material causes charge separation across the device, producing an electric field and consequently voltage drops proportional to the stress applied. The oscillating system is typically a cantilever beam structure with a mass at the unattached end of the lever. This structure provides higher strain for a given input force[17]. The voltage produced varies with time and strain, effectively producing an irregular AC signal on the average. Piezoelectric energy conversion produces relatively higher voltage and power density levels than the electromagnetic system. There are many applications based on piezoelectric materials, such as electric cigarette lighter. In this system pushing the button causes a spring loaded hammer to hit a piezoelectric crystal and the high voltage produced injects the gas slowly as the current jumps across a small spark gap. Following the same idea, portable sparkers used to light gas grills and stoves, and a variety of gas burners have built-in piezoelectric based ignition systems.

Table 2. Peak frequencies and accelerations of vibration sources.

Vibration Source	**Freq. of Peak (Hz)**	**Peak Accel. (m/s^2)**
Kitchen Blender Casing	121	6.4
Clothes Dryer	121	3.5
Door Frame (just after door closes)	125	3
Small Microwave Oven	121	2.25
HVAC Vents in Office Building	60	0.2-1.5
Wooden Deck with People Walking	385	1.3
Bread Maker	121	1.03
External Window (size 2ft x 3ft) next to Busy Street	100	0.7
Notebook Computer while CD is Being Read	75	0.6
Washing Machine	109	0.5
Second Story of Wood Frame Office Building	100	0.2
Refrigerator	240	0.1

Building environments are common places for vibrations caused by human power, wind, sound, and other sources. These common places include floors, ceilings, windows, air ducts, home appliances, staircases, and some machinery. These vibration sources were investigated and summarized by Leland, Lai, and Wright (2005) in Table 2[18]. A comparison of the amount of peak frequencies and peak accelerations was generated from a variety of vibration sources and reported.

Light Energy (Solar Energy): A photovoltaic cell has the capability of converting light energy into electrical energy[19,20]. Each cell consists of a reverse biased pn+-junction, where the light crosses with the heavily conservative and narrow n+ region. Photons where the light energy exists are absorbed within the depletion region, generating electron-hole pairs. The built-in electric field of the junction immediately separates each pair, accumulating electrons and holes in the n+ and p- regions, respectively, establishing in the process an open circuit voltage. With a load connected, accumulated electrons travel through the load and recombine with holes at the pside, generating a photocurrent that is directly proportional to light intensity and independent of cell voltage.

Human Power: Researchers have been working on many projects to generate electricity from human power such as exploiting, cranking, shaking, squeezing, spinning, pushing, pumping, stepping, and pulling[21]. For example some types of flashlights were powered with wind-up generators in the early 20th century[22]. Later versions of these devices, such as wind-up cell phone chargers and radios, became available in the market place. For instance, commercially available Freplay's (a commercial company) wind up radios make 60 turns in one minute cranking which allows storing of 500 Joules of energy in a spring. The spring system drives a magnetic generator and efficiently produces enough power for about an hour of play.

Thermal (Thermoelectric) Energy: Thermal gradients in the environment are directly converted to electrical energy through the Seebeck (thermoelectric) effect as reported by Disalvo[23] (1999); and Rowe[24] (1999). Temperature changes between opposite segments of a conducting material result in heat flow and consequently charge flow since mobile, high-energy carriers diffuse from high to low concentration regions. Thermopiles consisting of n- and p-type materials electrically joined at the high-temperature junction are therefore constructed, allowing heat flow to carry the dominant charge carriers of each material to the low temperature end, establishing in the process a voltage difference across the base electrodes. The generated voltage and power is relative to the temperature differential and the Seebeck coefficient of the thermoelectric materials. High thermal gradients are essential to produce practical voltage and power levels[25].

Wind Power: Wind power is the conversion of wind energy into a useful form, such as electricity, using wind turbines. At the end of 2007, worldwide capacity of wind-powered generators was 94.1 gigawatts[26]. Globally, wind power generation increased more than fivefold between 2000 and 2007[27]. The principle application of wind power is to generate electricity. Large scale wind farms are connected to electrical grids. Individual turbines can provide electricity to isolated locations. In the case of windmills, wind energy is used directly as mechanical energy for pumping water or grinding grain. Wind energy is plentiful, renewable, widely distributed, clean, and reduces greenhouse gas emissions when it displaces fossil-fuel-derived electricity. Therefore, it is considered by experts to be more environmentally friendly than many other energy sources. The intermittency of wind seldom creates problems when using wind power to supply a low proportion of total demand. Where wind is used for a moderate fraction of demand, additional costs for compensation of intermittency are considered to be modest[28].

III. Research Questions

A variety of questions and concerns especially stated by the students during the initial meetings of the project were explored. Some questions were answered by the course instructors but the remaining questions remain unanswered. The answers to these remaining questions will be derived from the experimental project phases until the final phase of the project is complete. The following research questions are the impetus of this study:

1. How self sufficient and energy efficient will the house be?

2. How consistent are the energy sources from day light to dark and between seasons?

3. What will be a viable type of electrical energy storage device?

4. Which energy conservation methods are compatible with energy sources?

5. What is the overall cost of an efficient, energy self sufficient design compared to that of conventional house design?

6. Are the energy costs of the self sufficient design lower than that of conventional energy costs using the same house design?

7. What is the overall cost to maintain the energy harvesting and storage devices on regular basis?

8. Do ambient energy sources play a supportive role in charging batteries for electronic devices? If so, can energy costs can be reduced by eliminating frequent replacements of conventional storage devices.

IV. Methodology and Participation of Students

The methodology of this research is to study a house of the future intended to be a completely self sufficient, energy efficient, ambient energy powered that intended to generate enough energy to power the house appliances. A self powered and energy efficient house idea was investigated to explore ways to convert environmental sustainable energy sources into electrical energy.

Students from different major disciplines (construction management, design development, electronics, industrial management, industrial technology and engineering) were encouraged to participate in this project. The team leader (advisor) had set up meetings to organize working schedules, prepare progress reports, and define tasks used in conducting the research project. The Technology Building at _____ State University having, all necessary construction tools, will be used to construct a demonstration house in the second phase of the project. The Computer models of the house and self powered furniture and appliances are being designed using Computer Aided Design and Drafting software tools by the Design Development major students located in the _____ Building. The Electronics lab have been upgraded by purchasing new devices, computers, and design/simulation software packages for the purpose of this project. The upgrade will especially support the second phase of the project. Students majoring in Electronics would use equipments in the electronics laboratory located in the _____ Building for the electrical design, development, wiring, and testing of the electrical components prior to integration into the house.

Students involved in this project have been experiencing structured independent research, creative thinking, and hands on experiences that benefit their future career and further the current knowledge of alternative ambient energy sources. Most of the energy sources were defined by the students and are being investigated. During the investigation a variety of software simulation tools such as LMS AMESim[29], Matlab, NI Multisim[30] etc. would be used prior to hands-on construction. Each source of ambient energy have been assigned to a student or student groups according to their major/minor or individual interest.

Analysis of energy requirements will be conducted using detailed calculations. If energy gain will be adequate to offset daily energy consumption, then energy gain~~s~~ and loss ratios would be calculated. In the event that energy adequate for a self sufficient house is not achievable, the generated energy will be used to reduce overall energy consumption within the house. Assuming energy friendly products consume less energy; computer models of energy friendly home appliances will be developed by the design and development students using Computer Aided Design software tools such as Revit, AutoCAD, Pro Engineer, Inventor, etc.

Ambient (environmental) energy sources available were identified before design of the house to identify potential energy sources to be evaluated. Additionally, power consumption and modeling of appliances needs to be performed in order to design the house to obtain maximum energy efficiency.

The ambient energy collected from different sources were characterized as high, medium, and low power sources. Energy generation from solar, wind, and hydroelectric power sources were considered high power sources. Energy from pedaled chairs (new design) and tables (new design), fitness equipment, collected gray water (from sinks, bath and rain), and city water, and some furniture were considered medium power sources. Power from opening and closing of doors and cabinet drawers, floor vibrations, clocks, heat differences etc. were considered low power sources. All energy collected from aforementioned sources need to be converted to electrical energy and transferred into storage devices (batteries or supercapacitors) using special energy harvesting and conversion electric circuits.

V. Energy Harvesting Circuit Design

Since harvested energy manifests itself in irregular, random, low/medium-energy bursts, a power-efficient, discontinuous, intermittent energy harvesting and battery charger circuit would be required to transfer the energy from the devices’ energy source to the storage unit. All the components of the harvesting and storage unit charging circuit would be carefully selected to avoid major losses through the circuit; and the circuits would be protected from unexpected shorts and high voltages from the stray energy sources. Furthermore, a universal design for the energy harvesting circuits would be flexible to allow adjustment of storage unit charging voltage and current to accommodate different capacity storage devices.

Typical energy harvesting circuits need to be designed, developed, and implemented for the purpose of low/medium power ambient energy harvesting. The first type of circuit design for energy harvesting for low power sources is intended to accommodate all types of low power sources i.e. universal. Designing unique circuits for each ambient energy source is time and cost prohibitive. Electronics major students will be developing different types of circuits using a variety of circuit simulation program tools such as National Instruments’ Multisim, Linear Technology based LTspice/SwitcherCAD III[31] prior to the implementation of test circuits in the second phase of the project. The efficiency of circuits to capture waste mechanical energy through generators, piezoelectric materials etc. and the transmission of power to storage devices will be tested extensively using prototyping boards in the laboratory. Major energy losses are usually associated with electronics components and would be identified to circumvent possible problems with designs. The typical circuit/component losses found in bridge rectifier diodes, voltage divider resistors, MOSFETs, etc. are unavoidable. The selection of low loss/high efficiency devices such as Schottky diodes replacing full wave bridge rectifier diodes, result in less minimal loss and optimized circuit design. After all simulations and laboratory prototyping tests, PCBs (Printed circuit boards) will be designed and ordered from a PCB manufacturer.

VI. Potential Ambient Energy Sources

Energy sources listed in the following table show where potential ambient energy exist and will be captured. Some of the sources (such as solar, wind etc.) have already been investigated and energy is being converted and used in most of the locations as detailed in literature review.

Table 3. Potential Energy Sources

Kitchen	Thermoelectric[1]	Mechanical	Hydroelectric[2]	Piezoelectric	Solar	Airflow	Acoustic Noise	Wind	Geothermal	Vibrations	Human Power[3]	Magnetic Field
Cabinet Drawers		✓									✓	
Sink			✓									
Gray Water Drains			✓									
Dish washer	✓		✓									✓
Refrigerator	✓	✓		✓								
Range	✓			✓								
Faucet			✓									
Kettle	✓											
Toaster	✓											
Blender		✓										✓
Mixer		✓										✓
Bread Maker	✓	✓		✓								✓
Waste Disposer		✓		✓						✓		✓
Cooking Air Filter	✓	✓										✓
Oven	✓											
Coffee Maker	✓											
Microwave	✓											
Fan		✓				✓						
Bathroom												
Lavatory			✓									
Gray Water Drains			✓									
Faucet			✓									
Fan		✓				✓						
Toilet Reservoir			✓									
Bath / Shower			✓									
Washing Machine			✓									✓
Clothes Dryer	✓					✓		✓				✓
Hair Dryer	✓										✓	✓

Gym												
Adult Fitness Equipments		✓										
Children’s Fitness Equipments		✓										
Body Temperature	✓											
Human Power		✓										
Fitness Sneakers		✓		✓								
Dining												
Crankable Chairs (New Design)		✓										
Crankable Tables		✓										
Common												
Stairs		✓								✓		
Fire Place	✓											
Sleepers		✓		✓								
Shoes		✓		✓								
Sneakers		✓		✓								
Sewing Machine		✓										
Cabinet Drawers		✓										
Gray Water Drains			✓									
Doors		✓										
Floor		✓		✓						✓		
Internal Solar					✓							
Keyboard		✓										✓
Mouse		✓										
Noise (Human, Pet, other sound)							✓					
Crankable Chairs		✓										
TV							✓					
Crankable Tables		✓										
Lazy Boy		✓										
Couch & Sofa		✓										
Bed		✓										
Roof & Outdoors												
Wind Turbines		✓						✓				
Vehicle (Car etc)	✓	✓			✓			✓				
Rain Water		✓	✓									
Sun					✓							
Noise (Human, Pet, other small sounds)							✓					
Geothermal									✓			
Roof vents		✓				✓						

Roofing Material	✓											

[1] (Heat Differences, Temperature Variations)
[2] (Gray Water System, Potable Water, Rain Water, Water Pressure)
[3] (Active and Passive)

VII. Implementation of the Energy Sources

The methods of power generation from ambient energy sources for self sustaining house are detailed below for each energy source.

Solar: The use of high efficiency solar cells/panels will be used to generate electricity. Solar collectors will be used to supplement the hot water system.

Wind: Wind generator technology will be used to generate electricity.

Furniture (Chairs, Tables, Carpets): Design and development major students will propose new energy generating chair and table designs. Thoughts are for active human power using crank shaft systems adapted to chairs and tables and using piezoelectric carpet fibers to generate electricity.

Doors & Drawers: The motion of doors and drawers will be translated to rotating motion and used to drive small generators for producing electricity.

Floors, Stairs: Vibrations from walking on a floor will be detected by piezo devices and converted to electricity.

Fitness equipments: The motion of many types exercise equipment (stationary bikes, static treadmills, stair climbers, etc.) will be translated to rotating motion and used to drive generators.

Clock mechanisms: A wind-up clock mechanism stores energy that will be used to drive small generators for long durations. A pendulum clock mechanism with extra heavy weights can exert larger amounts of torque therefore driving a larger generator will be used for producing electricity.

Rainwater: Energy from guttered rain water falling thru a downspout will drive a small generator to produce electricity. The water will be captured in a tank and used for yard watering. Water released from the tank, will drive a small generator to produce electricity.

Potable water system: Public water supplies pump water into elevated storage tanks to maintain positive pressure on the public water system. A positive displacement, rotary vein type drive device, attached to a generator, will be placed in the main supply line to the house. As water is consumed in the house, the flow of water will cause the device to produce electricity. Likewise, similar devices will be attached to the supply lines of various water consuming devices (toilets, lavatories, sinks, showers and tubs, washing machines, etc.) in the house to generate electricity.

Gray water system: Devices similar to those used in producing electricity from guttered rainwater can be applied to the gray water systems in a house(lavatories, sinks, and washing machines, etc.) and likewise can be converted into electricity.

Thermoelectric generation: The heat of a roof will be used to affect thermoelectric devices and materials to generate electricity. Thermoelectric generators will be used to convert differential water temperatures between solar heated water and tap water into electricity.

VIII. Selected Energy Conservation Methods

Energy conservation methods are detailed below.

Windows: The use of liquid crystal technology to filter light coming though window glass will reduce solar heating within the house thereby reducing cooling energy needs. Low emissive ("Low E") glass coatings reduce ultraviolet rays entering the structure and thereby house heating resulting in lower cooling energy requirements.

Insulated Concrete Forms (ICFs): ICFs offer greater "R" values for wall systems and thereby reduce heat loss or gain within the structure thereby saving air conditioning energy requirements.

Structural Insulated Panels (SIPs): Like insulated concrete forms, SIPs offer greater "R" values for wall and roof systems and thereby reduce heat loss or gain within the structure but at lower material cost than ICFs.

LED Lighting - Light Emitting Diodes: (LEDs) are low power electric lighting devices with great life expectancies. Use of LED lighting will reduce the amount of electric power conventionally needed for a house. Light emitting diodes have been implemented to light structures and have proved more efficient than incandescent or even fluorescent bulbs in a watt per lumen ratio. It will be hypothesized and eventually tested as to how effective such a lighting system is and what costs for consumption, initial investment and different ways to power them work out best.

Solar Lighting: During daytime hours, solar lighting using skylights and light pipes will reduce the need for conventional electric lighting.

Rainwater collection: Rainwater will be collected for future non-potable uses such as yard watering.

IX. Significance of Results

Ambient energy sources (small scale and decentralized renewable energy sources in particular), will let individuals and communities create and consume energy locally. The promotion of renewable energy sources by home owners, has brought a particular focus to the passive and active use of natural energy sources. Through the useful combination of natural energy, better insulation, energy efficient facilities, and greenery around the house; residents will enjoy greater comfort with less energy use. Results of this experimental project determine if the house can be self sufficient and energy efficient after completion of all phases. The intense experimental research will determine the most viable energy storage devices for the self sustained house construction. Construction cost of this energy efficient house project will determine if this project is a viable alternative to conventional house design. A new generation of energy efficient house devices and furniture that are capable of generating electricity with the help of human power will be designed, tested and demonstrated as future commercial devices. Most importantly, these types of projects will lead to reduction of power generation air pollutants like that from nuclear and coal power plants that have harmful effects on human beings and the environment. The construction of the energy sufficient/efficient house and the design of self powered devices will inspire many commercial companies to produce new products to fit self powered house needs.

X. Conclusion

The first phase of this experimental project is complete with great engagement and participation by the technology students. The students have defined the potential ambient energy sources available, during regularly scheduled project meetings. Email distribution lists/groups are being used to communicate with students according to their interest groups and to track the amount of work accomplished at the time of the email communication. As a second phase of the project, a small wood frame structure is being constructed using conventional construction techniques and materials. This will allow exploration and experimentation with the integration of potential energy harvesting and energy conservation techniques used for final design considerations.

A new alternative energy class is being designed for the technology program. Most of the research was explained in this research will be part of the class. This class will be offered beginning the Spring 2010 semester.

For the second phase of the project additional expenses for necessary supplies and equipments are being sought after through internal/external grant sources. The expected date of completion and final report of the project is June 2010. The detailed report of each energy source will be shared with academia and industry at the end of the project.

The identified sources will lead to further research of designing and building actual house to test all the sources were proposed in this research study.

XI. Future Work

For efficient energy generation, conversion, and storage; the energy conversion and storage circuits would be developed and tested for each energy source by the Electronics major students. Most importantly a unique energy conversion circuit needs to be developed for all the sources in order to decrease the overall cost of the project. All the sources will be investigated individually and extensively for maximum energy generation. The shortest path from the ambient energy source to storage device is needed to avoid voltage drops in the wires. For the purpose of placing storage devices closer to every energy source, a detailed routing investigation will be conducted.

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